

# LORENTZ SYMMETRY, THE SME, AND GRAVITATIONAL EXPERIMENTS

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This proceedings contribution summarizes the implications of recent SME-based investigations of Lorentz violation for gravitational experiments.

## 1 Introduction

General Relativity along with the Standard Model of particle physics provide a remarkable description of known physics. Lorentz symmetry is a foundational principle of each, and thus should be well tested experimentally. It is also likely that General Relativity and the Standard Model are limits of a more fundamental theory that provides consistent predictions at the Planck scale. Tests of Lorentz symmetry provide a technically feasible means of searching for potential suppressed signals from the Planck scale in existing experiments and observations.<sup>1</sup> The gravitational Standard-Model Extension (SME) provides a comprehensive test framework for searching for such potential signals across all areas of known physics.<sup>2,3</sup>

In spite of both the many high-sensitivity investigations of Lorentz symmetry<sup>4</sup> performed in the context of the SME in Minkowski spacetime,<sup>3</sup> the scope of which continues to deepen and broaden,<sup>4,5,6</sup> and the many investigations of metric theories of gravity performed in the context of the Parametrized Post-Newtonian (PPN) formalism,<sup>7</sup> there remain numerous potential Lorentz-violating deviations from General Relativity that have not yet been sought observationally and experimentally. Some of these violations would lead to qualitatively new types of signals.

Lorentz-violating effects in gravitational experiments can originate from two basic places: the pure-gravity action and gravitational couplings in the other sectors of the theory. While some distinct theoretical issues are associated with each origin, and some of the associated experimental signatures are quite different, the relevant effects can be observed in many of the same classes of experiments. The pure-gravity sector was the subject of Ref. 8, and Sec. 2 summarizes some of the key theoretical issues associated with that work. Section 3 provides a similar summary of theoretical issues associated with matter-gravity couplings, which were the subject of Ref. 9. Experiments relevant for investigations of Lorentz violation originating from both sectors are then considered in Sec. 4.

## 2 Lorentz violation in pure gravity

Investigations of Lorentz violation performed in the context of the minimal SME in Minkowski spacetime are extended to include the post-Newtonian implications of Lorentz violation in the

pure-gravity sector in Ref. 8, and several associated theoretical and phenomenological investigations have expanded aspects of that work.<sup>10,11</sup> The action for the minimal pure gravity sector takes the form<sup>2</sup>

$$S = \frac{1}{2\kappa} \int d^4x e (R - uR + s^{\mu\nu} R_{\mu\nu}^T + t^{\kappa\lambda\mu\nu} C_{\kappa\lambda\mu\nu}), \quad (1)$$

where  $C_{\kappa\lambda\mu\nu}$  is the Weyl tensor,  $R_{\mu\nu}^T$  is the traceless Ricci tensor, and  $e$  is the vierbein determinant. The first term here is the standard Einstein-Hilbert term. The relevant Lorentz-violating signals in the post-Newtonian analysis to follow stem from the third term involving the coefficient field  $s^{\mu\nu}$ . The second term is not Lorentz violating, and the fourth term provides no contributions in the post-Newtonian analysis.

It has been shown that in the present context of Riemannian spacetime, consistent Lorentz symmetry breaking must be spontaneous,<sup>2</sup> though use of more general geometries may admit explicit breaking.<sup>12</sup> A number of implications stemming directly from spontaneous symmetry breaking can also be considered,<sup>13,14,15</sup> however, a detailed discussion of these issues is beyond the scope of the present discussion.

As a result of the specialization to spontaneous symmetry breaking in the present context, a primary theoretical issue addressed in Ref. 8 is establishing a procedure for correctly accounting for the fluctuations in the coefficient fields, including the massless Nambu-Goldstone modes of Lorentz-symmetry breaking.<sup>13</sup> This challenge is met in a general way, without specializing to a specific model of spontaneous symmetry breaking, under a few mild assumptions. Upon addressing this issue, the leading-order Lorentz-violating contributions to the linearized field equations are obtained and can be expressed in terms of the metric fluctuation  $h_{\mu\nu}$  and the vacuum value  $\bar{s}^{\mu\nu}$  associated with the coefficient field  $s^{\mu\nu}$ . The post-Newtonian metric is obtained from these equations. With a suitable gauge choice<sup>8</sup> the metric takes the form

$$g_{00} = -1 + 2U + 3\bar{s}^{00}U + \bar{s}^{jk}U^{jk} - 4\bar{s}^{0j}V^j + O(4), \quad (2)$$

$$g_{0j} = -\bar{s}^{0j}U - \bar{s}^{0k}U^{jk} - \frac{7}{2}(1 + \frac{1}{28}\bar{s}^{00})V^j + \frac{3}{4}\bar{s}^{jk}V^k - \frac{1}{2}(1 + \frac{15}{4}\bar{s}^{00})W^j \\ + \frac{5}{4}\bar{s}^{jk}W^k + \frac{9}{4}\bar{s}^{kl}X^{klj} - \frac{15}{8}\bar{s}^{kl}X^{jkl} - \frac{3}{8}\bar{s}^{kl}Y^{klj}, \quad (3)$$

$$g_{jk} = \delta^{jk} + (2 - \bar{s}^{00})\delta^{jk}U + (\bar{s}^{lm}\delta^{jk} - \bar{s}^{jl}\delta^{mk} - \bar{s}^{kl}\delta^{jm} + 2\bar{s}^{00}\delta^{jl}\delta^{km})U^{lm}, \quad (4)$$

where  $U$ ,  $U^{jk}$ ,  $V^j$ ,  $W^j$ ,  $X^{klj}$ , and  $Y^{klj}$  are potentials formed from appropriate integrals over the source body. The explicit form of the potentials is provided in Ref. 8.

The above metric is then compared and contrasted with the PPN metric. The basic idea is that the pure-gravity sector of the minimal SME provides an expansion about the action of General Relativity, while the PPN provides an expansion about the metric. Perhaps surprisingly, an overlap of only one parameter is found between the 20 coefficients in the minimal pure-gravity sector of the SME and the 10 parameters of the PPN formalism. This implies that leading corrections to General Relativity at the level of the action do not match those typically studied in an expansion about the metric. Note also that the focus of the SME is on Lorentz violation throughout physics, while the focus of the PPN is on deviations from General Relativity, which may or may not be Lorentz violating. Thus the minimal pure-gravity sector of the SME and the PPN formalism provide complementary approaches to studying deviations from General Relativity.

Finally, Ref. 8 introduces bumblebee models<sup>16</sup> that provide specific examples of complete theories with spontaneous symmetry breaking that fit into the post-Newtonian results established in the general context of the SME.

### 3 Lorentz violation in matter-gravity couplings

Though many high-sensitivity investigations of Lorentz violation<sup>4</sup> have been performed in the context of the fermion sector of the minimal SME in Minkowski spacetime,<sup>3</sup> there remains a

number of coefficients for Lorentz violation in that sector that have not been investigated experimentally. A methodology for obtaining sensitivities to some of these open parameters by considering gravitational couplings in the fermions sector of the SME is provided by Ref. 9. The set of coefficients  $\bar{a}_\mu$  for baryons and charged leptons, which are unobservable in principle in Minkowski spacetime, is of particular interest. Due to gravitational countershading,<sup>17</sup> these coefficients could be large relative to existing matter-sector sensitivities.

Prior to developing the necessary results for experimental analysis, the theoretical portion of Ref. 9 addresses a number of useful conceptual points. One such point is consideration of the circumstances under which relevant types of Lorentz violation are observable in principle. Though the  $\bar{a}_\mu$  coefficient can be removed from the single fermion theory in Minkowski spacetime via a spinor redefinition, it is highlighted that it cannot typically be removed in the presence of gravity.<sup>2</sup> This results in the gravitational countershading pointed out in Ref. 17.

A coordinate choice that can be used to fix the sector of the theory that defines isotropy is also discussed, and the role of the gravitational sector in this context is established. Ultimately, the photon sector is chosen to have  $\eta_{\mu\nu}$  as the background metric, though no generality is lost, and other choices can be recovered.

The treatment of the fluctuations in the coefficient fields established for the gravitational sector is adapted to the context of matter-gravity couplings. Two notions of perturbative order are introduced to treat the fluctuations perturbatively under the assumptions that gravitational and Lorentz-violating corrections are small. One notion of perturbative order, denoted  $O(m, n)$ , tracks the orders in Lorentz violation and in gravity. Here the first entry represents the order in the coefficients for Lorentz violation, and the second entry represents the order in the metric fluctuation  $h_{\mu\nu}$ . A secondary notion of perturbative order, which tracks the post-Newtonian order, is denoted  $PNO(p)$ . The  $O(1, 1)$  contributions are of primary interest in Ref. 9, since the goal of that work is to investigate dominant Lorentz-violating implications in matter-gravity couplings.

To proceed toward the analysis of relevant experiments, the results necessary for working at a number of energy levels are developed from the full field-theoretic action of the gravitationally coupled fermion sector of the SME, which takes the form

$$S_\psi = \int d^4x \left( \frac{1}{2} i e e^\mu_a \bar{\psi} \Gamma^a \overleftrightarrow{D}_\mu \psi - e \bar{\psi} M \psi \right). \quad (5)$$

where

$$\begin{aligned} \Gamma^a \equiv & \gamma^a - c_{\mu\nu} e^{\nu a} e^\mu_b \gamma^b - d_{\mu\nu} e^{\nu a} e^\mu_b \gamma_5 \gamma^b \\ & - e_\mu e^{\mu a} - i f_\mu e^{\mu a} \gamma_5 - \frac{1}{2} g_{\lambda\mu\nu} e^{\nu a} e^\lambda_b e^\mu_c \sigma^{bc} \end{aligned} \quad (6)$$

and

$$M \equiv m + a_\mu e^\mu_a \gamma^a + b_\mu e^\mu_a \gamma_5 \gamma^a + \frac{1}{2} H_{\mu\nu} e^\mu_a e^\nu_b \sigma^{ab}, \quad (7)$$

where  $a_\mu$ ,  $b_\mu$ ,  $c_{\mu\nu}$ ,  $d_{\mu\nu}$ ,  $e_\mu$ ,  $f_\mu$ ,  $g_{\lambda\mu\nu}$ ,  $H_{\mu\nu}$  are coefficient fields for Lorentz violation.

Starting from Eq. 5, the relativistic quantum mechanics in the presence of gravitational fluctuations and Lorentz violation is established after investigating two methods of identifying an appropriate hamiltonian. The explicit form of the relativistic hamiltonian involving all coefficients for Lorentz violation in the minimal fermion sector is provided.

The standard Foldy-Wouthuysen procedure is then employed to obtain the nonrelativistic quantum Hamiltonian. At this stage, attention is specialized to the study of spin-independent Lorentz-violating effects, which are governed by the coefficient fields  $(a_{\text{eff}})_\mu$ ,  $c_{\mu\nu}$  and the metric fluctuation  $h_{\mu\nu}$ . Though interesting effects may exist in couplings involving spin, gravity, and Lorentz violation, the pursuit of spin-independent effects maintains a reasonable scope focused on the least well-constrained coefficients including the countershaded  $\bar{a}_\mu$  coefficients.

For many relevant applications, the classical theory<sup>18</sup> associated with the quantum-mechanical dynamics is the most useful description. Thus the classical theory involving nonzero  $(a_{\text{eff}})_\mu$ ,  $c_{\mu\nu}$ , and  $h_{\mu\nu}$  is established at leading order in Lorentz violation for the case of the fundamental particles appearing in QED as well as for bodies involving many such particles. The modified Einstein equation and the equation for the trajectory of a classical test particle follow from the classical theory. Obtaining explicit solutions for the trajectories of particles requires knowledge of the coefficient and metric fluctuations. A systematic procedure for calculating this information is established, and general expressions for the coefficient and metric fluctuations are obtained to  $\mathcal{O}(1,1)$  in terms of gravitational potentials and the vacuum values  $(\bar{a}_{\text{eff}})_\mu$  and  $\bar{c}_{\mu\nu}$  associated with the coefficient fields  $(a_{\text{eff}})_\mu$  and  $c_{\mu\nu}$ . With this, we find that the equation of motion for a test particle can be written

$$\begin{aligned} \ddot{x}^\mu = & -\Gamma_{(0,1)}^\mu{}_{\alpha\beta} u^\alpha u^\beta - \Gamma_{(1,1)}^\mu{}_{\alpha\beta} u^\alpha u^\beta + 2\eta^{\mu\gamma} (\bar{c}^{\text{T}})_{(\gamma\delta)} \Gamma_{(0,1)}^\delta{}_{\alpha\beta} u^\alpha u^\beta \\ & + 2(\bar{c}^{\text{T}})_{(\alpha\beta)} \Gamma_{(0,1)}^\alpha{}_{\gamma\delta} u^\beta u^\gamma u^\delta u^\mu - \frac{1}{m^{\text{T}}} [\partial^\mu (\bar{a}_{\text{eff}}^{\text{T}})_\alpha - \eta^{\mu\beta} \partial_\alpha (\bar{a}_{\text{eff}}^{\text{T}})_\beta] u^\alpha, \end{aligned} \quad (8)$$

where the metric to be inserted into the Christoffel symbols is

$$g_{00} = -1 + 2 \left[ 1 + 2 \frac{\alpha}{m} (\bar{a}_{\text{eff}}^{\text{S}})_0 + (c^{\text{S}})_{00} \right] U + 2 \left[ \frac{\alpha}{m} (\bar{a}_{\text{eff}}^{\text{S}})_j + 2(c^{\text{S}})_{(j0)} \right] V^j - 2 \frac{\alpha}{m} (\bar{a}_{\text{eff}}^{\text{S}})_j W^j, \quad (9)$$

$$g_{0j} = \frac{\alpha}{m} (\bar{a}_{\text{eff}}^{\text{S}})_j U + \frac{\alpha}{m} (\bar{a}_{\text{eff}}^{\text{S}})_k U^{jk} - \left[ 4 + \frac{\alpha}{m} (\bar{a}_{\text{eff}}^{\text{S}})_0 + 4(c^{\text{S}})_{00} \right] V^j - \alpha (\bar{a}_{\text{eff}}^{\text{S}})_0 W^j, \quad (10)$$

$$g_{jk} = \delta^{jk} + 2 \left[ 1 - \frac{\alpha}{m} (\bar{a}_{\text{eff}}^{\text{S}})_0 + (c^{\text{S}})_{00} \right] U \delta^{jk} + 2 \frac{\alpha}{m} (\bar{a}_{\text{eff}}^{\text{S}})_0 U^{jk}. \quad (11)$$

and the fluctuations in the coefficient field  $(a_{\text{eff}})_\mu$  take the form

$$(\bar{a}_{\text{eff}}^{\text{T}})_\mu^{(1,1)} = \frac{1}{2} \alpha h_{\mu\nu} (\bar{a}_{\text{eff}}^{\text{T}})^\nu - \frac{1}{4} \alpha (\bar{a}_{\text{eff}}^{\text{T}})_\mu h^\nu{}_\nu + \partial_\mu \Psi. \quad (12)$$

Here the superscripts S and T indicate coefficients associated with the source and test bodies respectively, and a dot over a quantity indicates a derivative with respect to the usual proper time. The subscripts on the Christoffel symbols indicate the order in the small quantities that should be included in the given Christoffel symbol. The vacuum values  $(\bar{a}_{\text{eff}})_\mu$  and  $\bar{c}_{\mu\nu}$  can then be identified with the coefficients for Lorentz violation investigated in the Minkowski spacetime SME.

As in the pure-gravity sector, bumblebee models provide specific examples of the general results.

## 4 Experiments

### 4.1 Laboratory Tests

The effects of coefficients  $(\bar{a}_{\text{eff}})_\mu$ ,  $\bar{c}_{\mu\nu}$ , and  $\bar{s}_{\mu\nu}$  can be measured in a wide variety of experiments performed in Earth-based laboratories. Tests of this type that have been proposed or performed include gravimeter experiments, tests of the universality of free fall, and experiments with devices traditionally used as tests of gravity at short range.

Analysis performed in Ref. 8 for the case of  $\bar{s}_{\mu\nu}$ , and in Ref. 9 for  $(\bar{a}_{\text{eff}})_\mu$  and  $\bar{c}_{\mu\nu}$ , reveals that the gravitational force acquires tiny corrections both along and perpendicular to the usual free-fall trajectory near the surface of the Earth. Coefficients  $(\bar{a}_{\text{eff}})_\mu$  and  $\bar{c}_{\mu\nu}$  also lead to a modified effective inertial mass of a test body that is direction dependent, resulting in a nontrivial relation between force and acceleration. Both the corrections to the gravitational force and to the inertial mass are time dependent with variations at the annual and sidereal frequencies. In addition, corrections due to  $(\bar{a}_{\text{eff}})_\mu$  and  $\bar{c}_{\mu\nu}$  are particle-species dependent.

Based on the above discussion, laboratory tests using Earth as a source fall into 4 classes. Free-fall gravimeter tests monitor the acceleration of free particles over time, while force-comparison gravimeter tests monitor the gravitation force on a body over time. Both types of gravimeter tests are sensitive to  $(\bar{a}_{\text{eff}})_\mu$ ,  $\bar{c}_{\mu\nu}$ , and  $\bar{s}_{\mu\nu}$  coefficients. The relative acceleration of, or relative force on a pair of test bodies can also be monitored constituting free-fall and force-comparison Weak Equivalence Principle (WEP) tests respectively. Sensitivities to  $(\bar{a}_{\text{eff}})_\mu$  and  $\bar{c}_{\mu\nu}$  can be achieved in WEP tests. Relevant devices presently used for the above types of tests include experiments with falling corner cubes,<sup>19</sup> atom interferometers,<sup>20,21,22</sup> superconducting levitation,<sup>23</sup> tossed masses,<sup>24</sup> balloon drops,<sup>25</sup> drop towers,<sup>26</sup> sounding rockets,<sup>27</sup> and torsion pendula.<sup>28</sup> Refs. 8 and 9 provide specific predictions and estimated sensitivities for the above tests including a frequency decomposition of the relevant signal to which experimental data could be fit. Note that the effective WEP violation with periodic time dependence considered here is a qualitatively different signal that would likely have been missed in past WEP tests. One experiment of this type has already been performed using an atom-interferometer as a free-fall gravimeter.<sup>21</sup>

Variations of the above laboratory tests involving the gravitational couplings of charged particles, antimatter, and second- and third-generation particles are also studied in Ref. 9. Though they are very challenging experimentally, these tests can yield sensitivities to Lorentz and CPT violation that are otherwise difficult or impossible to achieve. Charged-particle interferometry,<sup>29</sup> ballistic tests with charged particles,<sup>30</sup> gravitational experiments with antihydrogen,<sup>31</sup> and signals in muonium free fall<sup>32</sup> are considered. Some features of antihydrogen tests are illustrated with simple toy-models limits of the SME.

Though less sensitive at present to the range-independent SME effects presently under discussion, systems in which both the source mass and the test mass are contained within the lab, such as those devices traditionally used as tests of gravity at short range, can also be considered. A search for  $\bar{s}_{\mu\nu}$  has been performed using a cantilever system<sup>33</sup> and a search for  $(\bar{a}_{\text{eff}})_\mu$  using a torsion-strip balance<sup>34</sup> have been performed using this approach. A proposal to measure  $\bar{s}_{\mu\nu}$  using a torsion pendulum with an asymmetric mass distribution also exists.<sup>8</sup>

#### 4.2 Satellite-Based Tests

Space-based experiments can offer unique advantages in testing gravitational physics<sup>35</sup> and in searching for Lorentz violation.<sup>36</sup> The WEP tests considered above are an example of a class of tests for which significant sensitivity improvements might be possible in space, due to the long free-fall times that may be attainable on a drag-free spacecraft. There are several proposals for such missions in the advanced stages of development, including the Micro-Satellite à traînée Compensée pour l'Observation du Principe d'Equivalence (MicroSCOPE),<sup>37</sup> the Satellite Test of the Equivalence Principle (STEP),<sup>38</sup> and the Galileo Galilei (GG) mission.<sup>39</sup> A WEP experiment with reach similar to that of STEP has also been suggested for the Grand Unification and Gravity Explorer (GaUGE) mission.<sup>40</sup>

Monitoring the relative motion of test bodies of different composition as they orbit the Earth inside of the spacecraft is the basic idea underlying these missions. Nonzero coefficients for Lorentz violation  $(\bar{a}_{\text{eff}}^w)_\mu$  and  $(\bar{c}^w)_{\mu\nu}$ , would result in material dependent orbits. Ref. 9 provides the differential acceleration of the test masses, decomposed by frequency, that are relevant for fitting data for each of the above proposed tests, and achievable sensitivities are estimated. As in the lab-based tests, the SME signals would be distinguished from other sources of WEP violation by the characteristic time dependences of the signals. A ground-based version of the GG experiment, Galileo Galilei on the Ground (GGG),<sup>39</sup> which is presently taking data, could also obtain sensitivities to Lorentz violation.

Another test with sensitivity to Lorentz violation that was made possible using a space-based platform is the gyroscope experiment, Gravity Probe B (GPB).<sup>41</sup> The geodetic or de Sitter

precession about an axis perpendicular to the orbit and the gravitomagnetic frame-dragging or Lens-Thirring precession about the spin axis of the Earth are the primary conventional relativistic effects for a gyroscope in orbit around the Earth. An analysis of such a system in the presence of  $\bar{s}_{\mu\nu}$  was performed in Ref. 8. It was found that additional Lorentz-violating precessions result, including a precession about an axis perpendicular to both the angular-momentum axis of the orbit and Earth's spin axis. A similar investigation considering the effects of  $(\bar{a}_{\text{eff}})_\mu$  and  $\bar{c}_{\mu\nu}$  is possible based on the theoretical work in Ref. 9, but it remains an open problem at present.

### 4.3 Orbital Tests

The search for anomalous effects on orbits provides a natural way of testing gravitational physics. References 8 and 9 consider tests that search for such effects via laser ranging to the Moon and other bodies, perihelion precession measurements, and binary-pulsar observations.

Lunar laser ranging provides extraordinarily sensitive orbital measurements.<sup>42</sup> Based on the detailed proposal to search for the effects of pure-gravity sector coefficient  $\bar{s}_{\mu\nu}$  provided by Ref. 8, some of the best existing constraints on several components of that coefficient have been placed using lunar laser ranging data.<sup>43</sup> A similar proposal to search for  $(\bar{a}_{\text{eff}})_\mu$  and  $\bar{c}_{\mu\nu}$  effects on the lunar orbit is made in Ref. 9. Ranging to other satellites in different orientations or of different composition could yield additional independent sensitivities.

Measurements of the precession of the perihelion of orbiting bodies<sup>44</sup> are also considered for the case of  $(\bar{a}_{\text{eff}})_\mu$  and  $\bar{c}_{\mu\nu}$  coefficients<sup>9</sup> as well as  $\bar{s}_{\mu\nu}$  coefficients.<sup>8</sup> Based on the established advance of the perihelion for Mercury and for the Earth, constraints on combinations of  $(\bar{a}_{\text{eff}})_\mu$ ,  $\bar{c}_{\mu\nu}$ , and  $\bar{s}_{\mu\nu}$  are placed. These constraints provide the best current sensitivity to  $(\bar{a}_{\text{eff}})_J$ , though it comes as a part of a complicated combination of coefficients.

Binary-pulsar observations complement the above solar-system tests by providing orbits of significantly different orientations.<sup>45</sup> Reference 8 contains detailed predictions for the effects of  $\bar{s}_{\mu\nu}$  on binary-pulsar systems. The effects of  $(\bar{a}_{\text{eff}})_\mu$  and  $\bar{c}_{\mu\nu}$  on such systems could also be investigated, but detailed observational predictions remain to be made.

### 4.4 Photon and Clock Tests

A final class of tests involves the interaction of photons with gravity as well as effects on the clocks typically associated with such tests. References 11 and 9 consider signals arising in measurements of the time delay, gravitational Doppler shift, and gravitational redshift, along with comparisons of the behaviors of photons and massive bodies for Lorentz violation in the pure gravity sector and matter sector respectively. Null redshift tests are also considered in Ref. 9 resulting in expected sensitivity to  $(\bar{a}_{\text{eff}})_\mu$  and  $\bar{c}_{\mu\nu}$  coefficients. Implications for a variety of existing and proposed experiments and space missions are considered.<sup>46</sup> An analysis of a variety of clocks has been performed and sensitivities to  $(\bar{a}_{\text{eff}})_\mu$  and  $\bar{c}_{\mu\nu}$  coefficients have been achieved.<sup>22</sup> Note that these results and proposals are in addition to the Minkowski spacetime clock experiments which have been performed on the ground<sup>4</sup> and could be improved in space.<sup>36</sup>

## 5 Summary

Existing sensitivities from the experiments and observations summarized above can be found in *Data Tables for Lorentz and CPT Violation*.<sup>4</sup> Expected sensitivities based on the proposals summarized above are collected in Table 6 of Ref. 8 and Tables XIV and XV of Ref. 9. These sensitivities reveal excellent prospects for using gravitational experiments to seek Lorentz violation. Of particular interest are the opportunities to measure the countershaded coefficients  $(\bar{a}_{\text{eff}})_\mu$  since these coefficients typically cannot be detected in nongravitational searches.<sup>17</sup> Thus the tests of Lorentz symmetry proposed in Refs. 8 and 9 offer promising opportunities to search

for signals of new physics, potentially originating at the Planck scale. The effects can be sought in existing, planned, or feasible experiments and in some cases provide experimental signatures that are qualitatively different from those sought to date.

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